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雑誌名	東北大学電通談話会記録
巻	87
号	1
ページ	244-245
発行年	2018-08
URL	http://hdl.handle.net/10097/00123524

修士学位論文要約（平成30年３月）

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A Study on Normally-Off GaN High Electron Mobility Transistor Structures

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A concept of gallium nitride floating-gate high electron mobility transistor (GaN FG HEMT), which fulfills normally-off characteristic and low on-resistance, has been suggested in this study. This transistor stores electrons at floating-gate, and the threshold voltage can be modulated. In this study, an additional injection-gate was newly introduced, so that a high electric field during electron injection can be avoided at a gate oxide. Moreover, a device design procedure to achieve high performance was also formulated. This procedure can be applied at different operating conditions and target performances.

1. Introduction

A GaN is one of the wide bandgap semiconductors (WBS). GaN power devices have high-speed and high-voltage properties compared to conventional Si power devices. Due to the wide bandgap of 3.4 eV, the critical electric field of GaN is 3.3 MV/cm, which is 3 times larger than Si, and the electron mobility of GaN is relatively higher than other WBS such as 4H-SiC. In addition, the electron mobility of 2000 cm^2/Vs can be utilized by employing high electron mobility transistor (HEMT) structure. However, a HEMT generally has a normally-off characteristic[1], whereas a power device needs a normally-off characteristic for safety of power electronics. To resolve this issue, several types of normally-off HEMT structure were suggested[2–4], however they have issues at a high on-resistance and a low value of threshold voltage.

In this study, a device structure of a normally-off GaN floating-gate HEMT (FG HEMT), which fulfills both low on resistance and normally-off characteristic was suggested. At the same time, the device design procedure was formulated to implement this device.

2. GaN Floating-Gate HEMT

To achieve normally-off property, a floating-gate (FG) structure was introduced. A FG has been commonly used in silicon memory devices[5]. In this FG HEMT, high electric field is applied at gate oxide to inject electrons into FG, and it would cause reliability issues, therefore a tunnel oxide is separated, and an injection gate was newly introduced as shown in Fig. 1. To inject electrons into the FG, a negative voltage is applied at the injection-gate (IG), and electrons are injected by using Fowler-Nordheim tunneling mechanism. Besides, the suggested structure has newly introduced reverse L-shape FG to increase the coupling ratio between FG and control-gate (CG), hence the controllability by CG can achieve almost the same as conventional GaN HEMT. In the following section, Basic formula and principle of threshold voltage controlling are explained.

A. Theory of Threshold Voltage Modulation

The FG voltage to turn-off the 2DEG channel is expressed as:

$$V_{\mathrm{FG\_TH}} = \varphi_{\mathrm{m}} - \varphi_{\mathrm{F}} - \frac{qAn_{\mathrm{2DEG}}}{C}, \qquad (1)$$

where $\varphi_{\mathrm{m/F}}$ is work function of FG and GaN respectively, A the area of gate oxide, C the capacitance between FG and the source, n_{2DEG} the channel density. Based on a capacitive model of FG HEMT as shown in Fig. 2, the required electric charges for turning-off transistor is calculated as:

$$Q = C_{\mathrm{I}}(V_{\mathrm{FG}} - V_{\mathrm{IG}}) + C_{\mathrm{C}}(V_{\mathrm{FG}} - V_{\mathrm{CG}}) + CV_{\mathrm{FG}}, \qquad (2)$$

where C_{I} is the capacitance of tunnel oxide, C_{C} that of block oxide, $V_{\mathrm{FG/CG/IG}}$ is the voltage at the FG, CG, and IG respectively. Based on this, the threshold voltage V_{TH} (control-gate voltage at the threshold condition) is:

$$V_{\mathrm{TH}} = \frac{1}{C_{\mathrm{C}}}\left\{V_{\mathrm{FG\_TH}}(C_{\mathrm{I}} + C_{\mathrm{C}} + C) - C_{\mathrm{I}}V_{\mathrm{IG\_O}}\right\} - \frac{Q}{C_{\mathrm{C}}}, \qquad (3)$$

Here, it is found that the V_{TH} change by electron injection is expressed as $-Q/C_{\mathrm{C}}$.

B. Self-Limit Threshold Voltage Modulation

When enough Q is stored at FG and V_{TH} controlling is completed, the 2DEG channel is depleted and C includes the depletion capacitance of C_{D}. Therefore, the voltage between IG and FG would abruptly decrease, and the electron injection stops self-consistently. Practically speaking, it is found that the completion of V_{TH} controlling can be detected by monitoring the change of V_{IG}. This effect would contribute to control V_{TH} accurately and uniformly.

3. Design of GaN Floating-Gate HEMT

A design procedure of FG HEMT with injection-gate was formulated to achieve high performance. The procedure is illustrated as flow chart in Fig. 3. In this procedure, the operating voltage, the drain current and target on-resistance are firstly determined. Given the information of AlGaN/GaN substrate and oxide property, the acceptable leakage current and a critical electric field can be determined. After this, the dimension of gate length/width and gate-drain length is determined to obtain required drain current. Based on these steps, the on-resistance can be estimated, and these steps should be iterated until the on-resistance reaches the target value.

After these steps, the procedure of FG structure is conducted. For this, a large block oxide is firstly designed to obtain high coupling ratio. Secondly, the thicknesses of gate/block/tunnel oxides are determined. The thicknesses should be thin as much as possible to obtain high gate capacitance, and the thicknesses are chosen not to exceed the maximum limit of leakage current and electric field. Finally, the electric field distribution of the FG structure is checked. If there is serious electric field concentration at the FG, the shape of FG should be modified.

Based on this procedure, a floating-gate structure was designed as an example. It was designed to achieve high gate-controllability as much as GaN HEMTs. The given conditions were: V_{TH} = 3 V, the drain voltage V_D = 600 V, $Al_{0.22}Ga_{0.78}N$/GaN substrate (t_{AlGaN} = 20 nm) was considered. The block/tunnel oxide was SiO_2, and the gate oxide was Al_2O_3., and the maximum electric field of oxide was 5 MV/cm, AlGaN and GaN was 3.3 MV/cm, and maximum leakage current through oxides was 10^{-16} A/cm. By conducting the design, it was found that the gate oxide thickness is 4 nm, the block oxide is 26 nm, the tunnel oxide is 24 nm, and gate drain length is 13 μm. Besides, the coupling ratio was 75%, which means the channel resistance increases 133% compared to a GaN HEMT (the same t_{ox}, and L_{GD}). Even with this increase of channel resistance, the on-resistance of FG HEMT is still comparable to conventional GaN HEMT.

4. Conclusion

In this study, a concept of normally-off GaN FG HEMT was suggested. An independent injection-gate contributes device reliability. The self-limit V_{TH} modulation helps to control threshold voltage accurately and uniformly. A comprehensive design procedure of FG HEMT was also formulated, which helps to achieve high performance of GaN FG HEMT. Further analysis is required by fabricating actual devices.

Reference

[1] M.A. Khan, J.M. Van Hove, J.N. Kuznia, and D.T. Olson, Applied Physics Letters **58**, 2408 (1991).

[2] Y. Uemoto, M. Hikita, H. Ueno, H. Matsuo, H. Ishida, M. Yanagihara, T. Ueda, T. Tanaka, and D. Ueda, IEEE Transactions on Electron Devices **54**, 3393 (2007).

[3] H. Kambayashi, Y. Satoh, S. Ootomo, T. Kokawa, T. Nomura, S. Kato, and T. sing P. Chow, Solid-State Electronics **54**, 660 (2010).

[4] Yong Cai, Yugang Zhou, K.J. Chen, and K.M. Lau, IEEE Electron Device Letters **26**, 435 (2005).

[5] D. Kahng and S.M. Sze, Bell System Technical Journal **46**, 1288 (1967).

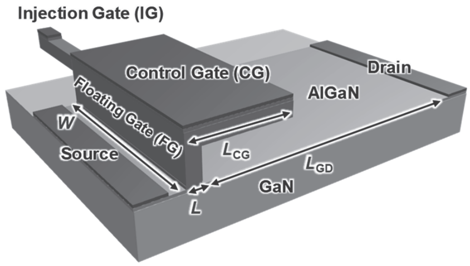

Figure.1 Structure of the GaN FG HEMT.

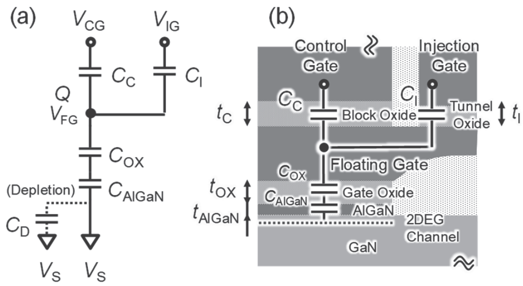

Figure.2 Capacitive model of FG structure.
(a) circuit model (b) Cross sectional view of gate.

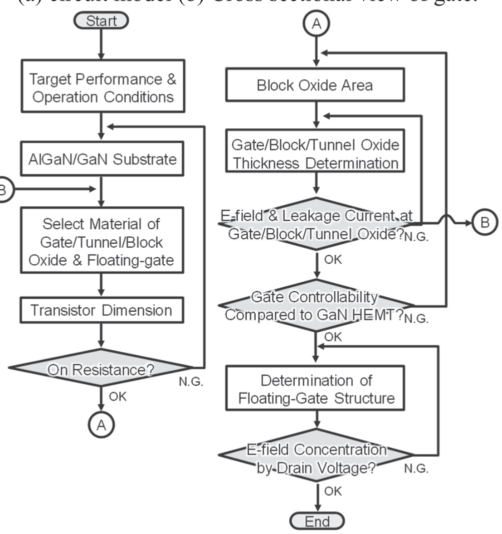

Figure.3 Comprehensive device design procedure.